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J/ψ polarization

from fixed-target to collider energies

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The determination of the magnitude and “sign” of the J/ψ polarization crucially depends on the reference frame used in the analysis of the data and a full understanding of the polarization phenomenon requires measurements reported in *two* “orthogonal” frames, such as the Collins-Soper and helicity frames. Moreover, the azimuthal anisotropy can be, in certain frames, as significant as the polar one. The seemingly contradictory J/ψ polarization results reported by E866, HERA-B and CDF can be consistently described assuming that the most suitable axis for the measurement is along the direction of the relative motion of the colliding partons, and that directly produced J/ψ ’s are longitudinally polarized at low momentum and transversely polarized at high momentum. We make specific predictions that can be tested on existing CDF data and by LHC measurements, which should show a full transverse polarization for direct J/ψ mesons of $p_T > 25$ GeV/ c .

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The existing measurements of J/ψ polarization in hadronic collisions represent one of the most difficult challenges currently faced by models of quarkonium production (see, for example, Refs. [1, 2] and references therein). The often emphasized disagreement between experiment and theory is, however, only one aspect of the problem. The experimental knowledge itself looks contradictory when different polarization measurements are compared, in terms of “sign”, magnitude and kinematic dependence, as illustrated in Fig. 1, which shows the data reported by CDF [2], HERA-B [3] and E866 [4].

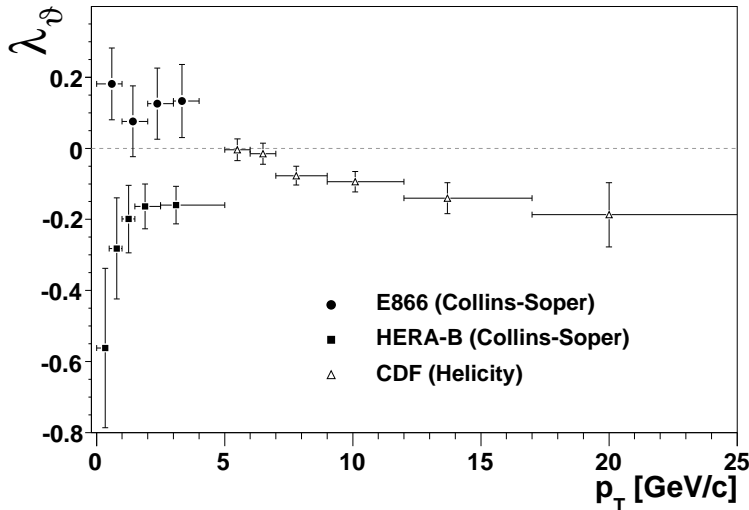


Figure 1: λ_θ versus p_T , as reported by E866, HERA-B and CDF (statistical and systematic errors added in quadrature).

Besides the obvious interest of understanding the mechanisms of quarkonium polarization, having a clear (data driven) description of the polarization measurements is also important to evaluate detector specific corrections needed to extract physics results from the data. Production cross sections, for instance, might significantly depend on the polarization scenario used in the calculation of acceptance corrections. The polarization measurements are undeniably complex and involve difficult experimental problems. There is, however, an additional cause for the blurred picture emerging from the comparison of the existing measurements: different experiments have often chosen different polarization frames to perform their analyses. The influence of such choices on the measured angular distribution of the decay leptons is generally underestimated. In fact, different analyses of *the same* two-body angular decay distribution may give qualitatively and quantitatively different results depending on the definition of the polarization frame.

Several polarization frame definitions have been used in the past. In the helicity frame the polar axis coincides with the flight direction of the J/ψ in the centre-of-mass frame of the colliding hadrons. A very different approach is implicit in the definition of the Collins-Soper [5] frame, where the polar axis reflects, on average, the direction

of the relative velocity of the colliding partons, the approximation being especially good if we can neglect the smearing effect due to the parton intrinsic transverse momentum. We denote by ϑ the angle between the direction of the positive lepton and the chosen polar axis, and by φ the azimuthal angle, measured with respect to the plane formed by the momenta of the colliding hadrons in the J/ψ rest frame (the “production plane”). The angular decay distribution, symmetric with respect to the production plane and invariant under parity transformation [5, 6], is usually defined as:

$$\frac{dN}{d(\cos \vartheta) d\varphi} \propto 1 + \lambda_{\vartheta} \cos^2 \vartheta + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi + \lambda_{\varphi} \sin^2 \vartheta \cos 2\varphi \quad (1)$$

If the J/ψ is observed in a given kinematic configuration, any two polarization frames differ only by a rotation around the axis perpendicular to the production plane (the “ y axis”). The functional dependence of the decay distribution on the angles ϑ and φ is invariant with respect to such a rotation, but the numerical values of λ_{ϑ} , $\lambda_{\vartheta\varphi}$ and λ_{φ} change in a correlated way. In particular, a rotation by the angle $\delta = 1/2 \arctan[2 \lambda_{\vartheta\varphi}/(\lambda_{\varphi} - \lambda_{\vartheta})]$ (or 45° when $\lambda_{\varphi} = \lambda_{\vartheta}$) leads to a frame where $\lambda_{\vartheta\varphi}$ is zero, i.e., a frame with axes along the principal symmetry axes of the polarized angular distribution. The experimental determination of $\lambda_{\vartheta\varphi}$ can, therefore, provide a criterion for the choice of a particularly convenient reference frame for the description of the angular distribution.

While all three coefficients provide interesting and independent information, most available measurements of J/ψ polarization are restricted to λ_{ϑ} . This limits the possible interpretations of the results and forces us to rely on model-dependent assumptions when comparing results obtained by experiments using different reference frames. Even the seemingly simple classification of “transverse” or “longitudinal” polarization¹ is, in fact, dependent on the reference frame. This is particularly evident when the decaying particle is produced with small longitudinal momentum, the Collins-Soper (CS) and helicity (H) polar axes becoming perpendicular to each other. In this case (assuming $\lambda_{\varphi} = \lambda_{\vartheta\varphi} = 0$, for simplicity), if in one frame we measure a value λ_{ϑ} , the value measured in the second frame is smaller and of opposite sign, $\lambda'_{\vartheta} = -\lambda_{\vartheta}/(2 + \lambda_{\vartheta})$, while an azimuthal anisotropy appears, $\lambda'_{\varphi} = \lambda_{\vartheta}/(2 + \lambda_{\vartheta})$.

There is a further reason for performing the experimental analyses in more than one reference frame. The J/ψ acquires its polarization with respect to a “natural” polarization axis which is, a priori, unknown and not necessarily definable event-by-event in terms of observable quantities. In practice, a fine-grained scan of the multidimensional phase-space of the J/ψ production process is not possible, due to the limited sample of collected events, which forces the decay distribution to be measured as an average over a wide spectrum of kinematic configurations. This means that the orientation of the polar axis of the chosen frame with respect to the “natural axis”

¹Following a common (albeit misleading) practice, the polarization is defined as transverse (longitudinal) when $\lambda_{\vartheta} > 0$ ($\lambda_{\vartheta} < 0$).

changes from event to event, depending on the momentum of the produced J/ψ . The resulting superposition of many distributions, equal in shape but randomly rotated with respect to one another, is “smeared” into a more spherically symmetric shape. As a consequence, the measured absolute values of λ_θ and λ_φ are smaller than what would be measured in a fixed kinematic configuration and in the “natural frame”. Therefore, independently of any prior theoretical expectation, the frame closest to the natural frame is the one providing the smallest δ angle *and* the most significant $|\lambda_\theta|$.

The HERA-B experiment recently reported the three coefficients determining the J/ψ decay angular distribution, in three reference frames [3], providing a clear picture of how the shape of the distribution changes from frame to frame. Before discussing kinematical dependences, we start by considering the values integrated in the phase space window covered by HERA-B: in the CS frame, $\lambda_\theta = -0.31 \pm 0.05$ and $\lambda_\varphi = -0.02 \pm 0.02$; in the H frame, $\lambda_\theta = -0.11 \pm 0.05$ and $\lambda_\varphi = -0.07 \pm 0.02$ (statistical and systematic errors added in quadrature). Furthermore, δ has a much larger error in the H frame ($10^\circ \pm 20^\circ$) than in the CS frame ($3^\circ \pm 3^\circ$), reflecting the poorer precision with which the “tilt” of a more spherically symmetric shape can be determined. With the largest $|\lambda_\theta|$ and a λ_φ compatible with zero, the CS frame is shown by the HERA-B measurements to provide a simpler angular distribution than the H frame.

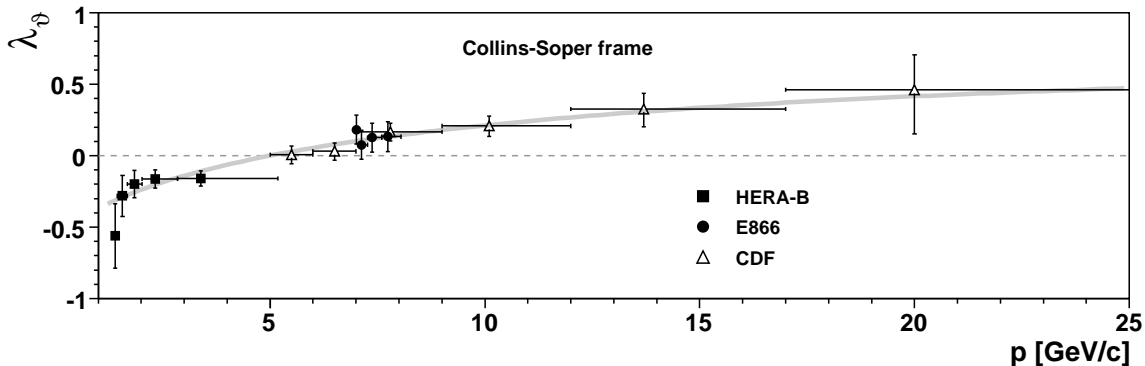


Figure 2: λ_θ as a function of p , from E866, HERA-B and CDF data (statistical and systematic errors added in quadrature).

We now address the kinematical dependence of the J/ψ polarization. Figure 1 shows that, in the CS frame, E866 [4] observed a small J/ψ transverse polarization ($\lambda_\theta \approx 0.1$) while the HERA-B pattern indicates longitudinal polarization, of decreasing magnitude with increasing p_T . These are not conflicting observations, given the significantly different x_F windows covered: the average J/ψ longitudinal momentum, in the centre of mass of the collision system, is 7 and -1.4 GeV/ c for E866 and HERA-B, respectively. Indeed, Fig. 2 shows that the *total* J/ψ momentum (here calculated using average x_F values) provides a good scaling between the two fixed-target data sets. As also shown in Fig. 1, CDF [2] reported that, above $p_T = 5$ GeV/ c , the J/ψ polarization is longitudinal in the H frame, with λ_θ steadily decreasing with p_T . To see how the CDF pattern compares to the fixed-target data sets, we need

to convert the published values to the CS frame. We did this translation (using the relations presented above) assuming that $\lambda_\varphi = 0$ in the CS frame, as suggested by the HERA-B measurements. The resulting pattern, seen in Fig. 2, is perfectly aligned with the HERA-B and E866 data points.

This smooth overlap of the three data sets suggests a simple polarization scenario, where the CS frame is taken to be a good approximation of the natural polarization frame ($\lambda_\varphi = 0$, $\lambda_{\vartheta\varphi} = 0$) and λ_ϑ is a monotonically increasing function of the total J/ψ momentum. Before searching a suitable function, we remind that a significant fraction of the observed J/ψ mesons results from χ_c and ψ' feed-down decays [7]: $f_{\text{fd}} = 0.33 \pm 0.05$. Irrespectively of the possible polarizations of these charmonium states, it is reasonable to assume that the strong kinematical smearing induced by the varying decay kinematics reduces the *observable* polarization of the indirectly produced J/ψ mesons to a negligible level. The feed-down contribution from b -hadron decays can also be neglected: very small at fixed-target energies and experimentally rejected in the CDF analysis. Therefore, the observed polarization should be essentially determined by the directly produced J/ψ 's. The curve in Fig. 2 represents a fit of all the data points using the simple parametrisation

$$\lambda_\vartheta = (1 - f_{\text{fd}}) \times [1 - 2^{1-(p/p_0)^\kappa}] \quad , \quad (2)$$

where the polarization of the *directly produced* J/ψ 's changes from fully longitudinal at zero momentum to fully transverse at asymptotically high momentum. The fit gives $p_0 = 5.0 \pm 0.4$ GeV/ c and $\kappa = 0.6 \pm 0.1$, with $\chi^2/\text{ndf} = 3.6/13$.

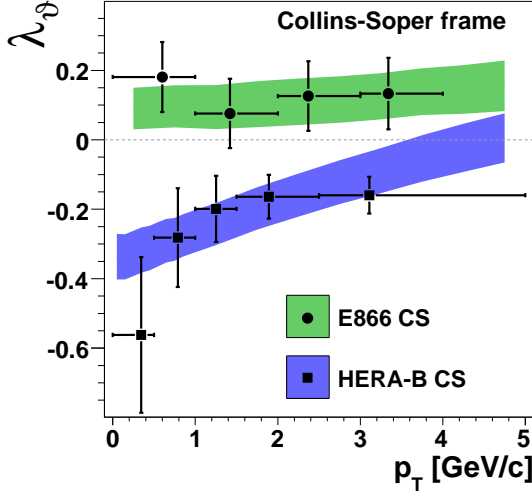


Figure 3: p_T dependence of λ_ϑ in the CS frame, according to Eq. 2 and as reported by E866 and HERA-B.

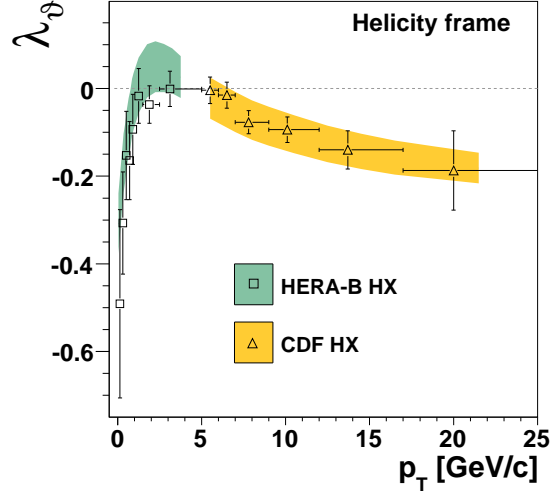


Figure 4: p_T dependence of λ_ϑ in the H frame, as derived from Eq. 2 and as reported by HERA-B and CDF.

Our simple parametrisation provides a good description of the existing data sets, as can be seen in Figs. 3 and 4, where the widths of the bands correspond to $\pm 1\sigma$

variations in the two fitted parameters as well as in the J/ψ feed-down fraction. The derivation of the λ_θ pattern in the H frame (needed, in particular, to address the CDF case) incorporates the “kinematical smearing” induced by the decays and the differential acceptances of the experiments (using a simple Monte Carlo procedure). In the narrow rapidity window of CDF, where the maximum J/ψ longitudinal momentum (~ 4 GeV/c) is always smaller than the minimum p_T (5 GeV/c), the helicity and Collins-Soper frames are essentially orthogonal to each other. Therefore, the decrease of λ_θ with p_T seen in the H frame (Fig. 4) is equivalent to an increase in the CS frame, as shown in Fig. 5.

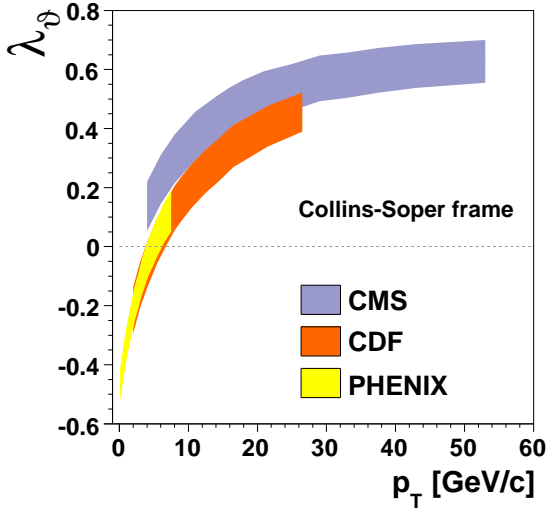


Figure 5: p_T dependence of λ_θ in the CS frame, calculated for the energy and rapidity windows of the PHENIX, CDF and CMS experiments.

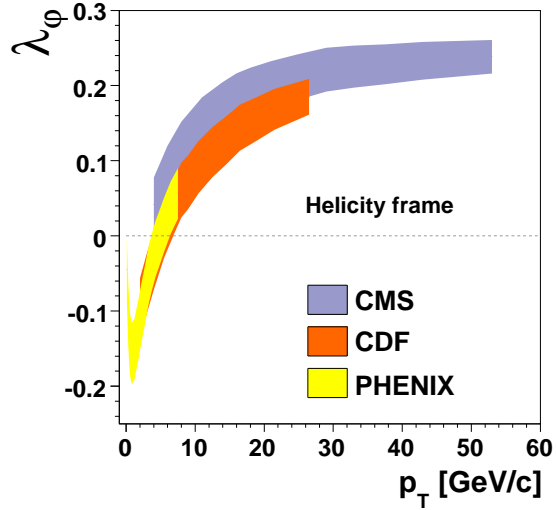


Figure 6: Same as previous figure, but for λ_ϕ in the H frame.

Assuming that the decay distribution has a purely polar anisotropy in the Collins-Soper frame, with λ_θ depending on momentum according to Eq. 2, CDF should observe a significant azimuthal anisotropy in the helicity frame, with a λ_ϕ pattern (shown in Fig. 6) similar in magnitude but of opposite sign with respect to their $\lambda_\theta(p_T)$ curve. By simply repeating the J/ψ polarization analysis using the CS frame and by reporting the azimuthal angular distribution, CDF can clarify whether the polarization of the J/ψ is, also at collider energies, induced along a direction close to the parton-parton interaction line.

Figures 5 and 6 also show the calculated p_T dependence of λ_θ , in the CS frame, and of λ_ϕ , in the H frame, for the kinematical conditions of the PHENIX ($\sqrt{s} = 200$ GeV, $|\eta| < 0.35$) and CMS ($\sqrt{s} = 14$ TeV, $|\eta| < 2.4$) experiments. If Eq. 2 remains valid up to LHC energies, we should see λ_θ saturating for p_T values higher than those probed by CDF, with a magnitude determined by the fraction of directly produced J/ψ mesons.

We will now summarise our main messages. 1) To investigate the J/ψ polarization and understand its origin, it is essential to know both the polar and azimuthal distributions, and their kinematical dependences, in at least two frames. The Collins-Soper and helicity frames, exactly orthogonal to each other at mid-rapidity, represent a good minimal set of polarization frames. 2) The HERA-B measurements show a pure polar anisotropy in the CS frame while a mixture of polar and azimuthal anisotropies is seen in the H frame, indicating that the J/ψ decay angular distribution assumes its simplest shape when observed with respect to a polar axis that reflects the relative momentum of the colliding partons rather than the J/ψ momentum. 3) The seemingly contradictory patterns published by E866, HERA-B and CDF can be consistently reproduced assuming that the polarization (in the CS frame) of the directly produced J/ψ mesons changes gradually from fully longitudinal at zero momentum to fully transverse at very high p . 4) This suggests that the longitudinal polarization reported by CDF in the H frame is, in fact, the reflection of a transverse polarization (around twice as large) in the CS frame, increasing with p_T . Moreover, an azimuthal anisotropy of the decay distribution should exist in the H frame, with the same significance as the polar result. 5) Our polarization scenario predicts that the polar anisotropy of the prompt J/ψ sample will saturate, for p_T above ~ 25 GeV/ c , at $\lambda_\vartheta \approx 0.6$ – 0.7 , a value determined by the magnitude of the ψ' and χ_c feed-down contributions, assumed to be of negligible observable polarization. This prediction, easily verifiable at the LHC, can be placed on more robust grounds once CDF reports the complete angular distribution in the CS frame or, at least, the azimuthal component in the H frame.

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